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10

Functional Gage Tolerancing

10.1 INTRODUCTION

Chapter 9 presents fundamentals of functional gage design implicitly assuming a tolerancing scheme. While the tolerancing rules may give a superficial appearance of being simple and easy to apply, some hidden concerns should be explicitly addressed. The driving force behind interest in these techniques is gaging policy. The original discussion starts in Chapter 5, where it is argued that a specific gaging policy must be selected and included as part of contractual obligations. There are also related discussions associated with measurement uncertainty and decision rules for determining conformance.

The following material illustrates methods that may be used to apply tolerances to functional gages. The examples suggest issues that must be pursued when real gages are to be built. At their root these issues involve the mechanics of implementing gaging policy and the resulting impact on acceptance rates. The risk associated with the final choice of policy can be reduced by an understanding of the implications of the different tolerancing techniques. Ultimately the decisions are economic in nature.

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10.2 GAGING ELEMENT SIZE AND MATERIAL MODIFIERS

Any physical gage requires selection of gaging element size, tolerances of size and geometry, and appropriate material modifiers. In an ideal world, the gage design would be derived from workpiece specifications using simple rules-of-thumb and quickly executed procedures. Unfortunately, simple rules inevitably have hidden consequences that should be considered when selecting the gaging policy.

A variety of gaging policies may be implemented when designing functional gages. The default policy in the United States might be considered to be absolute (pessimistic) tolerancing, as described in Sec. 5.6. This policy is intended to reject all part features not within specification.

There are costs, both apparent and hidden, associated with any tolerancing scheme. In the case of absolute tolerancing, a small percentage of borderline part features technically within tolerance may be rejected. This cost is considered to be acceptable in order to fulfill the policy's intent, to accept only good parts.

The following analysis is restricted to absolute tolerancing procedures and their effect on production yield. Similar analyses could be performed for the other tolerancing policy alternatives but are excluded for brevity. Included examples illustrate the range of results that occur when using the three material condition modifiers allowed by ASME Y14.5M. Each design choice results in a different conformance zone. The examples are used to verify whether a particular material condition choice in conjunction with absolute tolerancing succeeds in rejecting all out-of-tolerance parts (i.e., conforms to the gaging policy).

The design criteria driving the examples utilize the virtual condition boundary of the workpiece feature to establish one of the gaging element's boundaries—the inner locus boundary. The locus boundary concept is used to illustrate each example and discussed in some detail with an alternate approach to the analysis in Sec. 10.6. This gage boundary is the starting point in determining the acceptance region. The gage boundary is then used to calculate the gaging element size and appropriate tolerances based on the selected material condition modifier.

The functional gage examples are constructed for a prismatic part with four ∅.272-in. holes controlled with a positional tolerance using the maximum material condition (MMC) modifier (Figure 10-1). At one level the analysis could be based on statistical approaches that more closely model the actual variation that would be encountered. Because these are three-dimensional examples, the underlying variation would probably follow a multivariate statistical distribution. However, this introduces statistical and mathematical complications that are not easily resolved. It should suffice to say that such analysis is well beyond the intent of this book. Rather, the analysis model assumes that the positional errors of the

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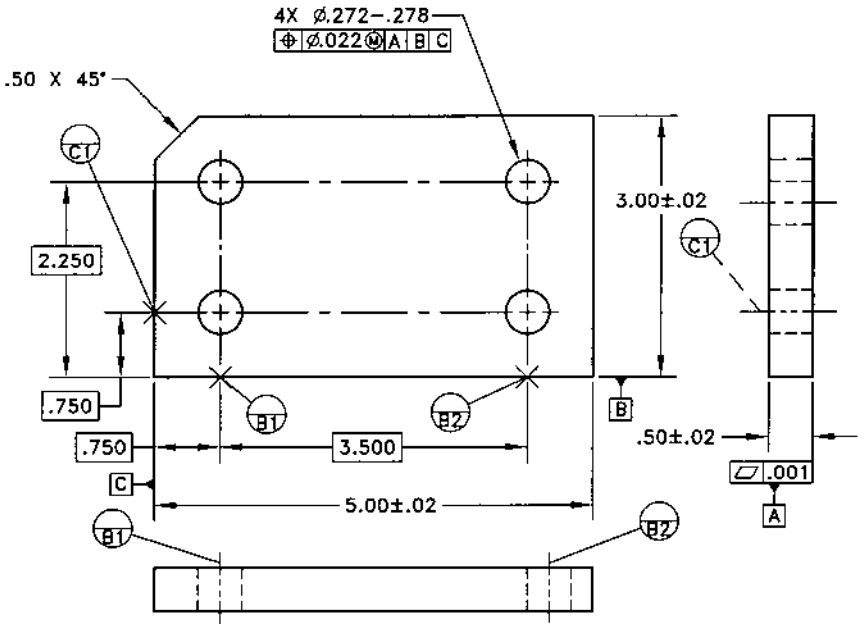

FIGURE 10-1 Workpiece example for gage analysis.

two mating features, the gage pin and the mating hole, are at their respective extremes (i.e., combinations of size and position). These extremes are then used to determine the range of part geometry the gage accepts.

There is little likelihood that the specific combination of positional errors illustrated in the examples will occur. These limiting values require not only that the extreme size and positional error values occur simultaneously on mating parts, but also that the positional errors of both features occur along the same line and with the same directional sense. While this particular combination of errors would seem to be of little practical consequence in view of its small probability of occurrence, the selected tolerancing policy (i.e., the absolute) purports to accept good parts and reject bad parts. With this in mind, it is appropriate to explore the limiting cases to see if the design rules meet the intent of the gaging policy and understand their limitations if the policy is not met. The goal is to be able to make informed choices when designing and building the gage.

10.3 WORKPIECE EXAMPLE

As mentioned, the workpiece used for the analysis is a prismatic part shown in Figure 10-1. The four holes drilled in the part are ∅.272 in., with a size tolerance

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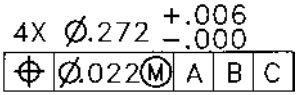
of +0.006 and −0.000. This size was chosen to take advantage of commercially available tooling (letter size drill H) and uses tolerance estimates for drilled holes cited by a number of sources (Truks, 1987). The four holes are completely located by basic dimensions within a datum reference frame.

The location controls are based on a floating fastener calculation using a 1/4-20 UNC fastener, with an MMC size of ∅.250. The floating fastener calculation yields

∅.272, MMC hole
−∅.250, MMC fastener
∅.022, positional tolerance

The complete callout for the four holes is



The size and positional callouts yield a part feature virtual condition equal to

virtual condition = MMC size of the hole
− geometric tolerance at MMC
virtual condition = ∅.272 − ∅.022 = ∅.250

The other boundary of concern is called the *resultant condition*. For this specific application, the resultant condition is calculated as follows:

resultant condition = LMC + geometric tolerance at MMC
+ difference in size between MMC and LMC
= ∅.278 + ∅.022 + ∅.006
= ∅.306

Both the virtual condition and resultant condition boundaries are used to evaluate gage effectiveness in the design cases analyzed ahead and in the appendix to this chapter.

All the examples assume the part features have been checked to determine if they are within the size specification. Only components that pass this first level of control are presented to the functional gage. The generic form of the functional gage looks like the illustration in Figure 10-2. Drawing details reflecting tolerance choice and modifier would be added to describe the completed gage after a dimensioning and tolerancing scheme is selected. At this point the figure is intended only to provide the general configuration of the functional gage that underlies each of the following examples.

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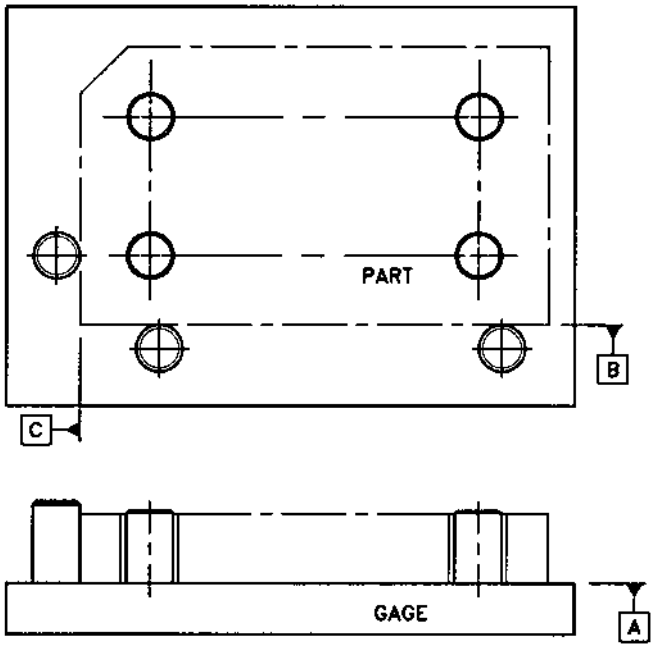

FIGURE 10-2 General form of gage used to inspect features of workplace.

The analyses in the next section and in the appendix (Secs. A10.1 through A10.4) show how to determine the theoretical conformance range created by a particular gage example. With the exception of size and position tolerance on the gage pin, this part of the chapter does not provide detailed comments on gage manufacturing issues. Sections 10.7 and 10.8 comment on manufacturing concerns that must be considered if a physical gage is to be fabricated, some having a direct impact on the design's effectiveness.

10.4 ZERO POSITIONAL TOLERANCE AT LMC

The first example uses the LMC modifier with a zero positional tolerance for the specification on the gage pin. The perfect gage pin is ∅.2500 when located at true position and at a basic 90° angle to datum A. This virtual condition size is the starting point to construct a physical gage element.

If a zero positional tolerance at LMC is applied to the gaging element, the total tolerance available to the gage pin—under one set of rules—becomes a combination of size and positional tolerance. The part tolerance is

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0.0060, the part's size tolerance

+0.0220, the part's positional tolerance at MMC

0.0280, total available part feature tolerance

As the gage element departs from LMC, the departure in size can be captured and used to accommodate position error. As a result, there is a one-to-one exchange between size departure from LMC and the available positional error allowed on the gage pin.

To calculate the tolerance on the gage pin, the ∅.028 total available tolerance on the part feature is used as the starting point to allocate a portion of total product tolerance to the gaging element. Using the traditional gagemaker's rule of 10%, the tolerance allocated to the gage pin is

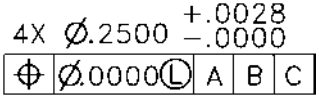
total feature tolerance × 0.10 = total gage element tolerance

For this particular example,

total tolerance on gage pin (size and position)

= 0.028 × 0.10 = 0.0028

The full ∅.0028-in. tolerance will be shown as the size tolerance on the gage pin. The complete callout for the gage pin is



We now explore the critical combinations of pin size and location that can be realized in building the gage. In all subsequent figures, the reference for the analysis is the true position of the part feature as indicated by "TP" in the diagrams.

10.4.1 LMC Gage Pin at True Position

This is an LMC pin located at true position. The pin size is ∅.2500, the virtual condition of the part features, and the gage pin boundary imposed by our design rule. In theory, this will accept parts at their virtual condition limit as established by specification.

10.4.2 MMC Gage Pin at True Position

This is a ∅.2528 pin that is larger than the virtual condition of the part feature being inspected and is located at true position. If the gage pin is fabricated at the MMC size, the gage pin will be ∅.0028 larger than the virtual condition size of the part feature established by the designer. In this situation, the gage will reject some parts that are actually within the acceptable range of design values—

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good parts are being rejected, those with generated boundaries falling between the part's virtual condition size (∅.2500) and the MMC gage pin at true position (∅.2528).

This range of values is controlled by the gage pin tolerance. At the relatively large pin tolerance—in gagemaker's terms—shown in the example, the tolerance on the pin could be reduced, still stay within the normal range of commercial components, and remain faithful to established gagemaker tolerance classes. At this nominal size (∅.250 in.), gagemaker tolerances run from 0.000020 in. (class XX) to 0.000100 in. (class Z). In this example, the gage designer has significant discretion to reduce the range of values within which good parts might be rejected by reducing the size tolerance of the pin.

10.4.3 MMC Gage Pin with Maximum Positional Error

With a gage pin fabricated at its MMC size, this case looks at a pin located at the maximum displacement from true position, ∅.0028, allowed by the gage design. This shift is illustrated in Figure 10-3 by displacing the gage pin center 0.0014 to the left. The figure illustrates the situation using radial values. With the exception of Secs. 10.6 and A10.4, all subsequent tolerance analyses use radial values for descriptive purposes.

Boundary of MMC pin (∅.2528)	0.1264
Shift of pin center allowed by maximum positional error	−0.0014
Distance from true positional to pin boundary	0.1250
Radius of LMC hole (∅.278)	0.1390
Distance from true position to pin boundary	−0.1250
Difference between true position and hole center	0.0140

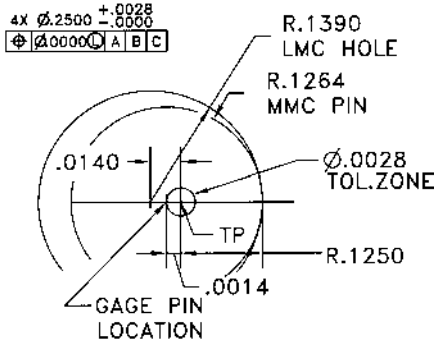

FIGURE 10-3 Functional gage with zero at LMC positional tolerance.

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TABLE 10-1 Gage Pin Sizes for Various Design Methods

Gage design method	LMC gage pin at true position	MMC gage pin at true position
Hole virtual condition	0.2500	0.2500
LMC—zero tolerance	0.2500	0.2528
RFS	0.2511	0.2522
MMC—10% rule	0.2500	0.2506
MMC—zero tolerance	0.2500	0.2528

The result, 0.0140, is the radial shift allowed to the center of an LMC hole on the part. This shift is with respect to the true position location and can be converted to the diametral tolerance zone for comparison with the part specification. The resulting diametral zone is

$$\text{positional tolerance zone} = 0.0140 \times 2 = \varnothing.0280$$

This matches the ∅.028 maximum positional tolerance allowed to the hole when it is fabricated at its LMC size.

10.5 RESULTS

The results of the preceding example and the remaining design alternatives explored in the appendix are summarized in Tables 10-1 and 10-2 and Figure 10-4. For purposes of discussion, gage effectiveness is defined as the proportion of the product specification that forms the conformance range established by the gage design. A gage design that allows use of a greater part of the specification range is more effective than a similar design using less of the specification range.

In theory, the LMC gage specification with a zero positional tolerance offers an effective design technique to implement the absolute gaging policy. Such a design accepts the virtual condition part if the gage pin is fabricated at its LMC size and located at true position. However, this requires a perfectly positioned LMC pin to become reality. Because such perfection is highly unlikely, manufac-

TABLE 10-2 Maximum Positional Error for Gage Pin at LMC and LMC Hole

Part specification	0.028
LMC Gage—zero tolerance	0.028
RFS Gage	0.028
MMC Gage—10% rule	0.0308
MMC Gage—zero tolerance	0.0308

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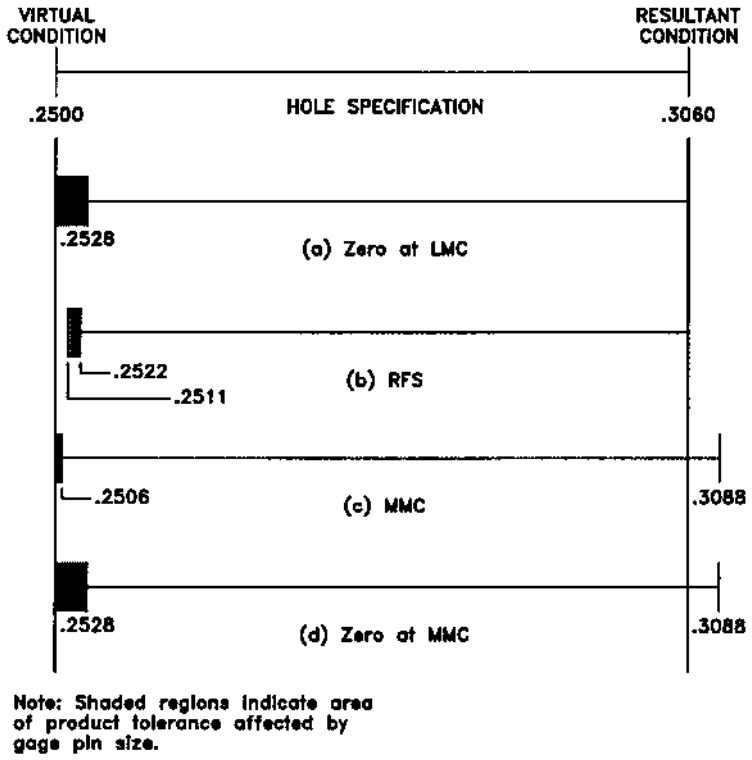

FIGURE 10-4 Results of tolerance analysis.

turing has to select the gage pin toward MMC size to make a nonzero positional tolerance value available for fabrication. At the opposite end of the specification range, the gage will not accept parts beyond the maximum positional tolerance of ∅.028 allowed by specification.

The RFS gage (Sec. A10.1) provides a somewhat less effective technique to achieve the same results as the LMC gage. The RFS gage will encroach into the part tolerance—the lower specification limit—in order to accept good parts and reject bad ones. To accomplish the latter, some good parts are rejected at the inner locus boundary (i.e., a true-position LMC gage element of ∅.2511 versus a part virtual condition of ∅.2500).

The MMC gage (Secs. A10.2 and A10.3)—using either 10% of the part's positional tolerance or a zero value for a gage tolerance—has similar characteristics as the RFS gage at the lower specification limit. These gage designs encroach on the part to an extent dictated by the finished size of the gage element. The designs match the virtual condition of the workpiece but allow acceptance of

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extreme parts (i.e., LMC holes at maximum positional error) outside specification.

10.6 ALTERNATE FORM OF ANALYSIS

Radial values are used in the examples to provide better graphical demonstration of the results. This is probably not the way it would be done by GD&T practitioners. The more likely analysis would use diametral calculations consistent with the typical cylindrical shape of the positional tolerance zone. To illustrate the more common approach, the example in Sec. 10.4 is repeated using more conventional methods. A similar example is found in Sec. A10.4. The calculations require determining an inner boundary of the gage pin and the outer boundary of the inspected hole. The resulting boundaries are more correctly referred to as locus boundaries. The term "locus" is used in its mathematical form as "the curve or other figure composed of all the points which . . . are generated by a point, line, or surface moving in accordance with defined conditions" (Oxford, 1993). The boundaries are related to the physical feature but are not limited to the obvious boundary that circumscribes part material. Detailed examples of boundary calculations for a variety of situations can be found in Meadows (1998).

The analysis requires calculation of the boundaries as follows:

$$\text{gage pin inner locus boundary} = \text{LMC} - \text{geometric tolerance specified at LMC}$$

For this example, the specified value of the geometric tolerance is zero at LMC size:

$$\text{gage pin inner locus boundary} = \varnothing.2500 - \varnothing.0000 = \varnothing.2500$$

The analysis also requires calculation of the outer locus boundary of the hole. Referring to the part specification, the size of the feature at LMC was $\varnothing.278$, the geometric tolerance was $\varnothing.022$, and the available bonus was $\varnothing.006$.

$$\text{hole outer locus boundary} = \varnothing.278 + \varnothing.022 + \varnothing.006 = \varnothing.306$$

This outer boundary value represents the boundary for a hole produced at maximum positional error allowed by specification. The intent of the following analysis is to determine if either of the two gaging cases meets this specification or deviates from the desired results.

The difference between the inner locus boundary of the pin and the outer locus boundary of the hole is used to establish the theoretical acceptance region of the gage. The tolerance range of workpiece accepted by the gage is illustrated

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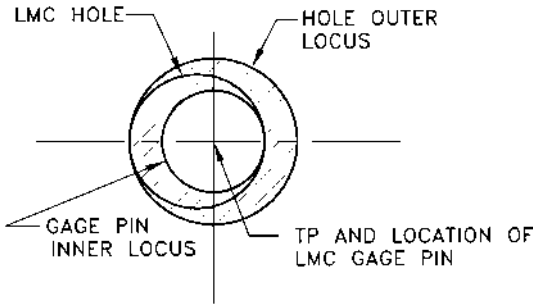

FIGURE 10-5 Functional gage analysis using diametral specifications.

in Figure 10-5. It shows the acceptance region created by these two boundaries and within which the inspected feature must lie. The actual displacement of the physical feature relative to the center of the gaging area (i.e., true position of the hole) depends on the combination of size and positional tolerance at which the gage pin and the hole are produced. The maximum displacement for this gage example occurs for the combination of a part produced at the LMC hole (∅.278) and an LMC gage pin with maximum allowed displacement from true position. The latter feature generates the gage pin's inner boundary.

Figure 10-5 takes the radial analysis methods and uses the equivalent diametral values. In the figure the inner boundary for the gage pin is located at the true position for the gage, which is also the true position of the hole. The intermediate-sized circle represents the LMC hole displaced the maximum distance allowed by the gage pin. The largest circle is generated when the LMC circle is rolled around the inner boundary gage pin. This outer circle is the locus of points described by the unusual combination of an LMC hole mating with an LMC gage pin, each with maximum positional error and shifted in direction and sense to create the worst-case situation. The combination yields

$$\text{maximum positional tolerance} = [2(\text{LMC hole} - \tfrac{1}{2}\ \text{gage pin's inner boundary})] - \text{LMC hole}$$

A little algebra shows that this reduces to an equation that yields the same results as the radial analyses:

$$\text{maximum positional tolerance} = \text{LMC hole} - \text{gage pin's inner boundary}$$

For a gage with zero tolerance specified at LMC,

$$\text{maximum positional tolerance} = \varnothing.278 - \varnothing.250 = \varnothing.028$$

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As anticipated, this numerical value matches the maximum positional tolerance allowed if the part feature is produced at LMC. Figure 10-5 illustrates this case and shows the acceptance region created by the design.

It should be mentioned that when this technique is applied to gage design using any feasible alternative specification, all critical combinations of size and tolerance should be investigated. It is the designer's responsibility to ensure that the consequences of the design are fully understood and that all parties reach a consensus on acceptability of the design.

10.7 FITS AND ALLOWANCES

While all of the examples have assumed a worst-case analysis with the parts mating at their respective virtual condition sizes, this technique may not be acceptable in all situations. Many products utilize specified fits and allowances to achieve the desired function. If the gage analysis involves a product that incorporates predetermined allowances, then the gage calculations must be altered.

Techniques can be developed to accommodate this situation. One approach that could be used involves allocating a portion of the allowance to each member of the mating pair. One of the authors helped a large manufacturer explore this type of technique. After extended discussion, the technical team decided to apply 40% of the allowance to each of the mating parts and retain 20% of the allowance as a buffer to ensure proper assembly.

10.8 BUILDING THE GAGE

At some point either a gage or a fixture will be built. This section looks at the ramifications in moving the gage design from concept to metal. The discussion is framed around our sample part (Figure 10-1) with a specific gage design used to illustrate tolerance considerations and their effect on gage fabrication.

10.8.1 Machine Tool Capabilities

In our example, fairly large tolerances have been specified. These values are consistent with the philosophy of providing justifiable tolerances that are as large as possible within functional requirements, providing manufacturing with as much latitude as feasible. The ∅.022-in. positional tolerance chosen for Figure 10-1 falls into the ISO fine tolerance category for clearance holes (floating-fastener case). Since most current machine tools are capable of holding tolerances to ±0.00011 in., they can locate bored holes for gage pins or bushings to positional tolerance diameters of 0.0003 in., far closer than needed to fabricate the gages illustrated in Figures 10-6 through 10-9. In addition, commercially available radial relief micro boring bars provide more than sufficient capability for the toler-

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ances specified in the workpiece and gage illustrations. These boring bars are designed for CNC porting applications that range in diameter from 0.015 to 0.490 in. The boring bars contain tenth-adjusting boring heads capable of moving the tool 0.00005 in. radially.

With this available technology, these gage designs may never come close to rejecting parts under any of the material conditions, because production machine tools have improved by at least an order of magnitude in the past 20 years. In the case of the example gages, the 10% rule may not make sense, as the clearance holes and gage pins may never make contact. As a consequence, little gage wear will likely occur.

Tolerances applied to the datum feature simulators on the gage are of paramount interest to the gage designer because of their effect in creating an apparent increase in part tolerance. These apparent increases in part tolerance may result as the gage departs from the perfect geometry by

Tolerances of form placed on gage surfaces
Tolerances of size, form, orientation, and location applied to features of size that comprise the fixture and gaging elements
Tolerances associated with relationships that create the DRF

When a part is assembled over the four ∅.2500-in. gage pins during inspection, the part datum targets must contact the three ∅.2000-in. dowel pins on the gage. The positional tolerances on these target pins may shift the part left to right if the tertiary datum pin is not the nominal size or at the basic location. The part may also translate up or down or assume an angular orientation if the two pins creating the secondary datum are not in line or the same size. The designer and the gagemaker should be alert to this situation. While this may appear as stating the obvious, it is a possible cause of part rejection if the three ∅.2000 dowel pins on the gage are not functional (i.e., not representative of mating part geometry). This functional consideration has been emphasized throughout the book, and it is expected that the designers are now well versed in the concept that gages should represent mating parts.

It is pointed out earlier in this chapter that there is a very small probability of occurrence associated with the worst-case situations used in the analyses. The basis for this conclusion is the random nature of the errors being considered. One caveat that should perhaps be mentioned is that once the gage is fabricated, the errors associated with a particular physical gage are no longer random in nature. Randomness is still present in the workpiece/gage system during the inspection process, but this effect is primarily due to the random distribution of errors associated with part manufacture, not due to random effects present in the physical gage. As a consequence, acceptance probabilities are affected by the state of the gage immediately following fabrication and during its useful life—hence the

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need for formal maintenance and calibration procedures to ensure adequate control of the gage or fixture.

The bilateral tolerancing system, which in effect dictates RFS on everything associated with the gage assembly, still appears to be the norm. At least one automotive company utilizes this method coupled with notes such as "10% not to exceed ± 0.12 mm" to place bounds on the available gage tolerances. The authors have found these RFS gage applications throughout industry with only one exception. This was at a government facility with extremely critical functional specifications imposed on manufacturing. The facility used LMC in a few applications but then discontinued the practice because the gage designers insisted that manufacturing worked only to bilateral tolerances at RFS. The same attitude was found in the automotive firm and makes it difficult to enforce GD&T on the tool drawings if these specifications are to be ignored.

Most gages are subsequently calibrated to bilateral tolerances (RFS). To the authors' knowledge, virtual condition has not been applied to gage feature calibration. It is possible that either actual local size or actual mating size is all that has been used in determining when a gage has worn out.

10.8.2 Single-Setup Gage Feature Manufacture

The control level that can be built into the finished gage is strongly influenced by the manufacturing process sequence. To illustrate this, two types of gages have been considered, fixed pin (case I) and removable pin (case II). In both design alternatives, the manufacture of these gages has been approached using the single-setup methods recommended by the authors. The accompanying design for the gage base shows a process DRF used to establish the inspection DRF. The former is composed of datum A, datum Y, and datum Z (see Figure 10-6). The inspection DRF is composed of datum A, datum B, and datum C, which are identified on the assembly drawings (Figures 10-7 and 10-8). The gage pins have been given tolerances to the minus side so that there will be no tolerance stackup.

The following operations provide gages for the workpiece shown in Figure 10-1.

Case I—Fixed-Pin Gage

Operation 1: Rough machine rectangular gage base to fit part in Figure 10-1.
Operation 2: Grind primary datum A to 0.0002 flatness. See Figure 10-6.
Operation 3: Clamp gage base on primary datum A, align, and machine surfaces Y and Z.
Operation 4: Zero machine tool off datums Y and Z for single-setup location of seven bores.

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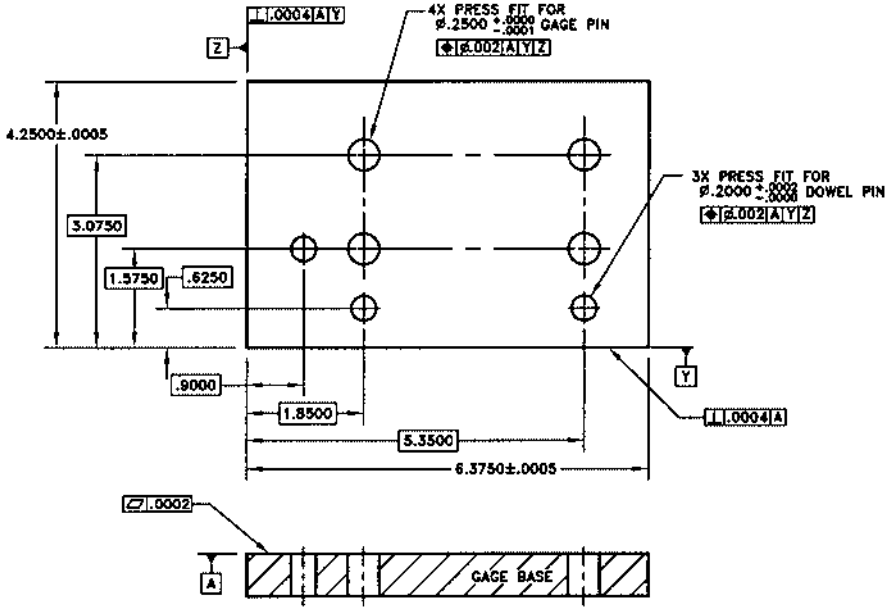

FIGURE 10-6 Gage base for single-setup manufacturing.

Operation 5: Drill and micro bore gage features for press fit of datum targets and gage pins.

Case II—Removable-Pin Gage Repeat operations 1 through 5, but drill and micro bore the four gage features for slip renewable bushings. These operations will suit an RFS, MMC, or LMC gage, but the gage pins will be sized for a clearance fit into the set of four commercial bushings.

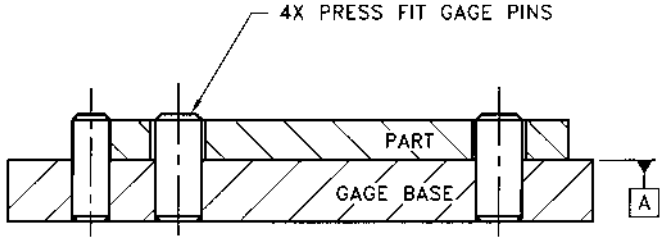

FIGURE 10-7 Gage and part assembly for case I.

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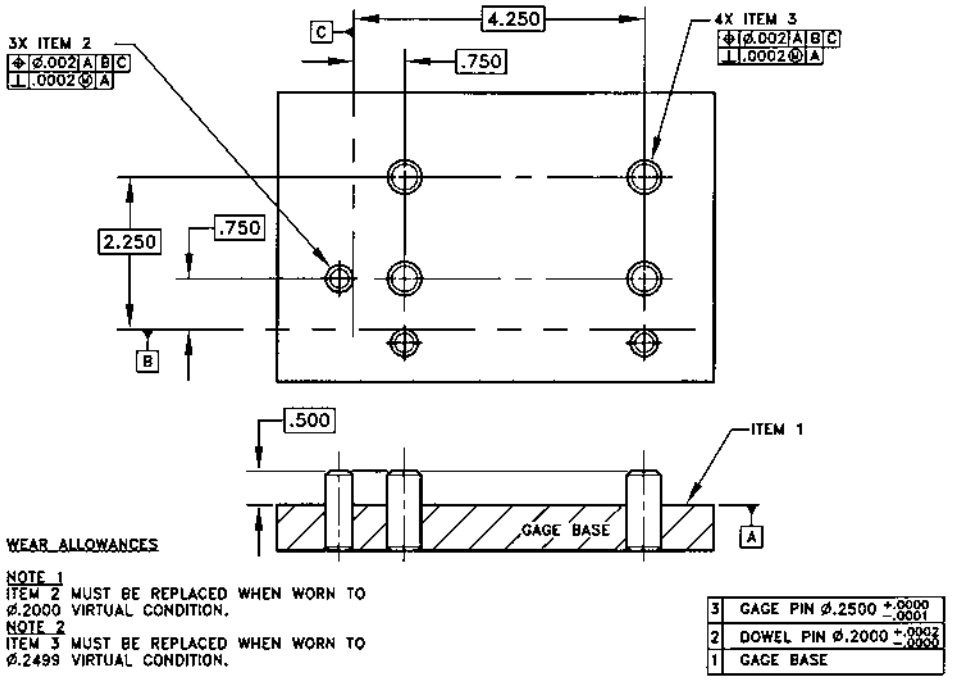

FIGURE 10-8 Gage assembly with calibration requirements (Case I).

10.8.3 Gage Assembly Operations

Case I—Fixed-Pin Gage

Operation 1: Place a set of ∅.2000- and ∅.2500-diameter gage pins in a freezer to soak.

Operation 2: Fit dowels and gage pins and press them into bores (Figure 10-7).

Operation 3: Check that dowel and gage pins are secure after soaking gage at 68°F.

Operation 4: Measure all pin locations and perpendicularity and record virtual condition.

Operation 5: Remove all pins that approach wear allowance.

Operation 6: Determine condition of wear allowance on each gage feature prior to use.

Operation 7: Determine calibration schedule on gages (Figure 10-8).

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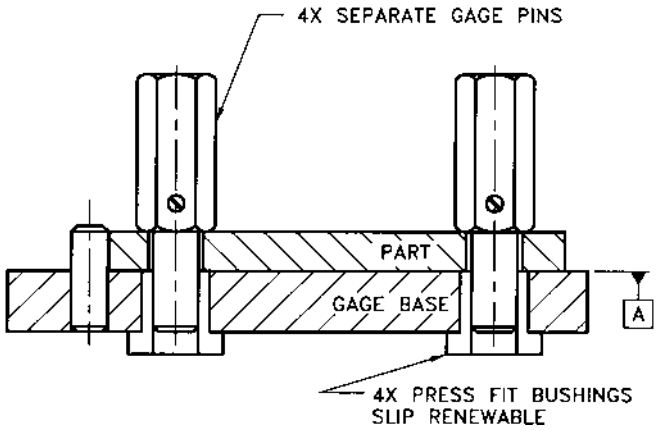

FIGURE 10-9 Bushed gage and part assembly for Case II.

Case II—Removable-Pin Gage Repeat assembly operations 1 through 3 using bushings. Each bushing should be measured in operations 4 through 7 with the gage pin inserted into the bushing and the gage base. This should be done with the gage base and pins at 68°F. Then proceed with operations 4 through 7. Finish by fitting handles on the four gage pins as shown in Figure 10-9.

The same operator on the same machine tool should fabricate all the gage bases. The positional tolerances (Figures 10-6 and 10-8) can be easily held with current machine tools that guarantee ±0.00011 in. Note that several backup gages should be provided.

10.9 SUMMARY

The results of the four examples are shown in Table 10-2 and Figure 10-4. In all of these examples, relatively large tolerances are shown for the gage. It is recognized that these gage tolerances may be reduced significantly and still remain in the realm of commercially available gaging components or standardized gagemaker tolerances. However the effects are still the same.

All the example gage design analyses are based on worst-case situations whose probability of occurrence is small. However, it is worth noting that once the gage is built, a unique combination of size, location, and direction of error is built into the gage pin and becomes fixed rather than random. As a consequence, the random effects of mating the hole with the gage are now generated only by the holes presented to the gage and wear characteristics of a specific physical gage.

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With the hole's virtual condition boundary used as the inner gage boundary, there is a gray zone at the lower specification limit where good parts may be rejected based on the actual gage pin size. The extent of this area is determined by the size and tolerance the gage pin is allowed as it is produced.

The LMC gage theoretically stays within the specification limits but requires an MMC size pin with the maximum positional error to accept parts made at the maximum positional tolerance for the hole (the hole resultant condition). Additionally, material must be added to the LMC pin to have any tolerance with which to make the gage. The result is that the conformance region is moved away from the lower specification limit.

The RFS gage protects the gaging policy by creating a conformance zone whose boundaries are contained inside the specification at the lower limit. The gage rejects technically good parts at the lower end of the specification zone to ensure that no bad parts are accepted.

The MMC gage with a nonzero positional tolerance meets the virtual condition boundary of the part with the gage pin at LMC. At the other end of the specification range, the MMC gage can accept parts larger than the hole's resultant condition—those parts with greater positional errors than allowed by specification. The extent of this situation depends on the size of the gage pin, the error associated with pin location, and the geometry of the hole presented to the gage.

An MMC gage with zero positional tolerance has a larger range where it may reject good parts when the gage pin is located at true position. This zone is created between the LMC size and the MMC size pin. At the other end of the specification range, this design technique has the same results as the MMC gage with a specified nonzero positional tolerance; it accepts parts with greater positional tolerances than allowed by specification.

There are many possible ways to calculate and partition tolerances. Each method will require analysis and documentation.

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Oxford University Press, The New Shorter Oxford English Dictionary, New York: Oxford University Press, 1993.

Truks, H. E., Designing for Economical Production, 2nd ed., Dearborn, MI: Society of Manufacturing Engineers, 1987.

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APPENDIX 10.A

To avoid bogging down the reader in details, the remaining analyses used in the chapter and necessary to the comparisons documented in Tables 10-1 and 10-2 and Figure 10-4 have been placed in this appendix. The LMC example in Sec. 10.4 is joined with the following alternatives to show the range of options available to the designer.

A10.1 RFS CALLOUT ON GAGE PIN

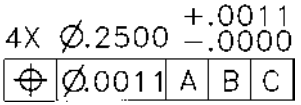
The part virtual condition is again used as the starting point to create the gage specification. A variety of tolerance combinations (size and position) could be used in creating the gage. Only two alternatives are examined here. The gage tolerances are developed by first utilizing 10% of the part feature's positional tolerance to establish possible gage tolerances of size and position.

$$\text{initial gage tolerance} = \text{part feature positional tolerance} \times 0.10$$

$$\text{initial gage tolerance} = 0.022 \times 0.10 = 0.0022$$

A10.1.1 First Trial

The first trial will treat this value (0.0022) as the sum of the size and positional tolerances on the gage pin. Letting the first trial share the tolerance equally between size and position, the gage pin callout becomes



At true position and using a ∅.2500 pin, the feature's virtual condition boundary is the same as the gage pin boundary; in theory, the ∅.2500 virtual condition hole will mate with a ∅.2500 gage pin.

However, if the LMC (∅.2500) gage pin is ∅.0011 out of position, the following situation results (Figure A10-1):

Boundary of LMC pin (∅.2500)	0.12500
Shift of pin center allowed by maximum positional error	−0.00055
Distance from true position to pin boundary	0.12445
Radius of LMC hole (∅.278)	0.13900
Distance from true position to pin boundary	−0.12445
Difference between true position and hole center	0.01455

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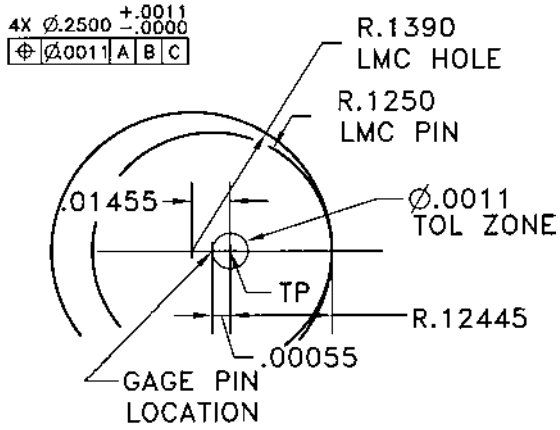


FIGURE A10-1 Functional gage with RFS positional tolerance, first trial.

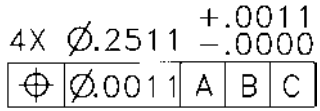
The result, 0.01455, is the radial shift allowed to the center of an LMC hole. This shift is with respect to the true position location and can be converted into the diametral tolerance zone for comparison with the part specification. The resulting diametral zone is

$$\text{positional tolerance zone} = 0.01455 \times 2 = \varnothing.02910$$

When compared to the ∅.028 maximum positional tolerance the hole is allowed when it is fabricated at its LMC size, this preliminary gage design will allow nonconforming parts to be accepted. The gaging combination of an LMC pin at its maximum allowable positional error checking an LMC hole on the workpiece does not meet the absolute criterion.

A10.1.2 Second Trial

In an attempt to improve the design of the RFS gage and protect the specification at the extremes circumstances, the gage's inner boundary can be enlarged. Here 0.0011 has been added to the size specification of the gaging element. The new specification is



Checking the effects of this gage pin and feature combination, one can investigate

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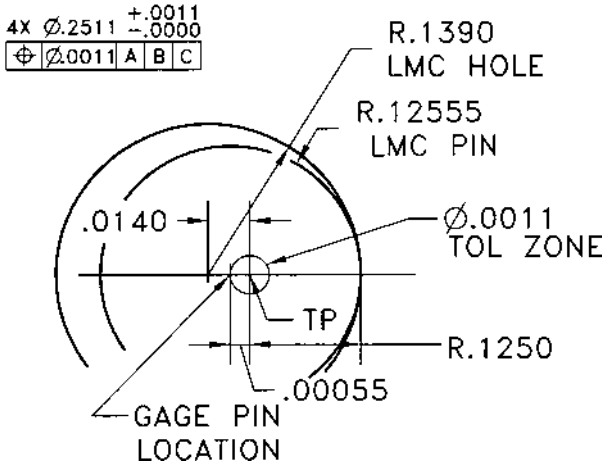

FIGURE A10-2 Functional gage with RFS positional tolerance, second trial.

the results with the gage pin at LMC with maximum positional error shown in the diagram (Figure A10-2).

Boundary of LMC pin (∅.2511)	0.12555
Shift of pin center allowed by maximum position error	−0.00055
Distance from true position to pin boundary	0.12500
Radius of LMC (∅.278) hole	0.13900
Distance from true position to pin boundary	−0.12500
Difference between true position and hole center	0.01400

The result, 0.01400, is the radial shift allowed to the center of an LMC hole on the part being inspected. This shift is with respect to the true position location and can be converted into the diametral tolerance zone for comparison with the part specification. The resulting diametral zone is

$$\text{positional tolerance zone} = 0.01400 \times 2 = \varnothing.0280$$

When compared to the ∅.028 maximum positional tolerance the part is allowed when it is fabricated at its LMC size, this second design will, in theory, accept parts within the design specification. However, it should be noted that this occurs only at the extreme inner boundary of the conformance region. Furthermore, this also requires that the gage be intentionally produced with a positional error that matches the maximum stated tolerance of position.

A different situation results if the gage is not produced with the intentional error mentioned, but is made with the LMC gage pin (∅.2511) at true position.

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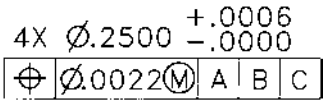
A gage with an LMC gaging element at perfect location will encroach into the virtual condition boundary—now described with a diametral rather than radial value—of the workpiece (∅.2500) by ∅.0011. In addition, this encroachment could be as large as ∅.0022 if the pin is still at true position but fabricated at its MMC size. The result is that the RFS callout may reject more "good" parts than the "zero at LMC" gage design.

A10.2 MMC CALLOUT ON GAGE PIN

Another possible approach to the specification of gaging elements is to use traditional gagemaker's tolerances with MMC callouts. For this example, application of the 10% rule could lead to the following gage pin specification:



A10.2.1 LMC Gage Pin at True Position

An LMC gage pin at true position is ∅.2500, the same as the virtual condition of the inspected feature. In theory, the LMC pin will match the virtual condition boundary of the workpiece and accept good parts while rejecting nonconforming parts.

A10.2.2 MMC Gage Pin at True Position

An MMC pin (∅.2506) at true position is ∅.0006 larger than the ∅.2500 virtual condition size of the mating hole on the workpiece. The result is that an MMC pin at true position could reject good parts between the workpiece virtual condition size of ∅.2500 and the MMC size of the pin, ∅.2506.

A10.2.3 Gage Pin at LMC and Maximum Positional Error

If the gage pin is fabricated at its LMC size and is out of position by the maximum positional tolerance allowed, the following situation (Figure A10-3) occurs:

Boundary of LMC pin (∅.2500)	0.12500
Shift of pin center allowed by maximum positional error	−0.00140
Distance from true position to pin boundary	0.12360
Radius of LMC (∅.278) hole on part	0.13900
Distance from true position to pin boundary	−0.12360
Difference between true position and hole center	0.01540

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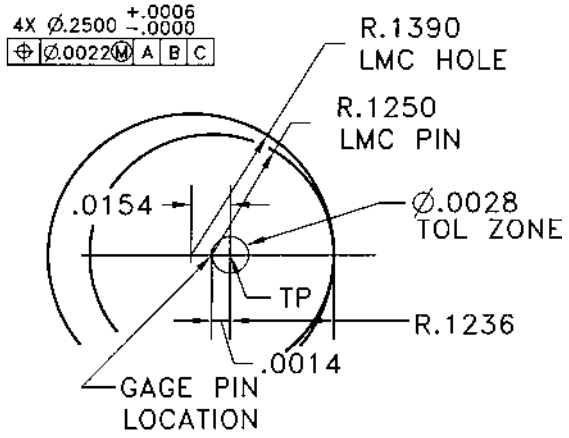


FIGURE A10-3 Functional gage with MMC positional tolerance.

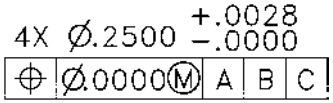
The result, 0.01540, is the radial shift allowed to the center of an LMC hole on the part being inspected. This shift is with respect to the true position location and can be converted into the diametral tolerance zone for comparison with the part specification. In this situation, the resulting diametral zone is

$$\text{positional tolerance zone} = 0.01540 \times 2 = \varnothing.0308$$

When compared to the ∅.0280 maximum positional tolerance the LMC hole is allowed, this gage design would allow nonconforming parts to be accepted.

A10.3 ZERO POSITIONAL TOLERANCE AT MMC

The last approach to specifying gaging elements is to use traditional gagemaker's tolerances with MMC callouts but specify a zero positional tolerance. The difference between this approach and that of Sec. 10.6 is that manufacturing has the ability to partition the total feature tolerance of ∅.0028 in any manner—size or position. Application of the 10% rule leads to the following gage pin specification:



A10.3.1 LMC Gage Pin at True Position

The LMC size gage pin is ∅.2500, the same as the virtual condition of the inspected feature. If the LMC pin is located at true position, in theory it will match

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the virtual condition boundary of the workpiece and accept good parts while rejecting parts that are out of specification.

A10.3.2 MMC Gage Pin at True Position

An MMC pin (∅.2528) at true position is ∅.0028 larger than the ∅.2500 virtual condition size of the mating hole on the workpiece. The result is that an MMC pin at true position will reject good parts between the workpiece virtual condition size of ∅.2500 and the gage pin MMC size of ∅.2528.

A10.3.3 LMC Gage Pin and Maximum Positional Error

If the gage pin is fabricated at its LMC size and is out of position by the maximum positional tolerance allowed, the following situation (Figure A10-4) occurs:

Boundary of pin LMC (∅.2500)	0.12500
Shift of pin center allowed by maximum positional error	−0.00140
Distance from true position to pin boundary	0.12360
Radius of LMC hole	0.13900
Distance from true position to pin boundary	−0.12360
Difference between true position and hole center	0.01540

The result, 0.01540, is the radial shift the center of an LMC workpiece hole is allowed. This shift is with respect to the true position location and can be con-

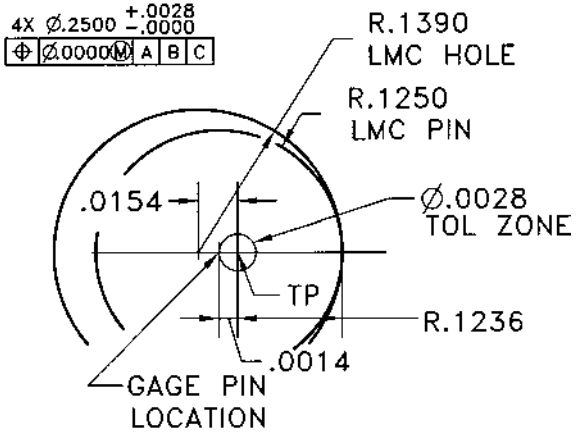

FIGURE A10-4 Functional gage with zero MMC positional tolerance.

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verted into the diametral tolerance zone for comparison with the part specification. In this situation, the resulting diametral zone is

$$\text{positional tolerance zone} = 0.01540 \times 2 = \varnothing.0308$$

When compared to the ∅.028 maximum positional tolerance the LMC hole is allowed, this gage design would allow out-of-specification parts to be accepted. To reiterate, the difference between this approach and the MMC design of the preceding section is the increased ability to exchange size and positional tolerance to optimize the manufacturing process.

A10.4 DIAMETRAL ANALYSIS—ZERO AT MMC GAGE

Revisiting the example in Section A10.3, the following conventional analysis would result: The LMC hole remains the same.

The inner boundary of the gage pin becomes

$$\text{gage pin's inner boundary} = \text{LMC} - \text{specified tolerance at MMC} - \text{difference in size between MMC and LMC}$$

$$\text{gage pin's inner boundary} = \varnothing.2500 - \varnothing.0000 - \varnothing.0028 = \varnothing.2472$$

$$\text{maximum positional tolerance} = \text{LMC hole} - \text{gage pin's inner boundary}$$

$$\text{maximum positional tolerance} = \varnothing.2780 - \varnothing.2472 = \varnothing.0308$$

This matches the values found in the earlier analysis. Figure A10-5 shows the effects of the MMC specification. Contrasting this with the LMC gage shows the additional shift allowed by the size specification of the gage pin. The result is that the acceptance region is enlarged when the fabricated pin departs from MMC size.

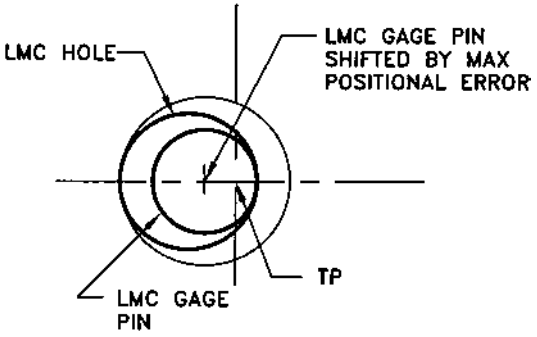

FIGURE A10-5 Functional gage analysis using diametral specifications.

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